

CORONAL STRUCTURES OBSERVED BY RADIO PROPAGATION MEASUREMENTS

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Abstract. This paper summarizes (1) advances in our knowledge of coronal structures inferred from radio propagation measurements, and (2) gains in our understanding of the relationship between radio propagation and white-light coronagraph measurements. Radio propagation measurements confirm that streamers are ray-like structures as depicted in coronagraph pictures, but also reveal a hierarchy of filamentary structures throughout the corona, extending from the size of streamers down to scale sizes as small as about 1 km at the Sun (10-3 arcsec). Doppler shift measurements, therefore, open a new window on small-scale structure that has long eluded coronagraph measurements. In addition, high precision ranging measurements make it possible to investigate large-scale structures not yet observed in coronagraphs, such as plumes in equatorial coronal regions.

1. INTRODUCTION

Radio propagation experiments, which were first conducted with natural radio sources as they passed behind the Sun and subsequently with coherent spacecraft radio signals, have been invaluable for probing the solar corona. They are crucial not only because they bridge the gap between solar measurements and the solar wind observed directly by spacecraft, but also because they observe the solar wind near its source, prior to evolution with radial expansion. Based on a wide variety of radio scattering and propagation phenomena, these observations yield measurements of electron density, electron density fluctuations, solar wind speed, and magnetic field. Examples of the observed radio phenomena include angular broadening, spectral broadening, intensity scintillation, Doppler/phase scintillation, ranging (or time delay) and Faraday rotation. Such

investigations have spanned four decades, during which reviews have been given by Erickson (1964), Hewish (1972), Jokipii (1973), Lotova (1975), Coles (1978), Woo (1979), Armand et al. (1987), Bird and Edenhofer (1990), Coles (1993), and Woo (1994).

Although considerable information has been obtained, especially with regard to density, solar wind speed, and the properties of the density fluctuations, radio propagation measurements have yielded little more than the radial (and in some cases latitudinal) dependence of these solar wind parameters in the corona, with scant information on their connection to solar features. Other aspects relating to these observations that until now have not been understood include the nature of the ubiquitous density fluctuations, the relationship of the density fluctuations (observed by Doppler scintillation for example) to density (observed by ranging measurements), and the connection between the radio propagation measurements and structures in the corona as depicted by white-light coronagraph measurements. The purpose of this paper is to review recent results that have contributed significantly to these issues.

II. RECENT RESULTS ON THE SOLAR CORONA

A breakthrough in understanding the solar corona observed by radio propagation measurements came when large variations in density fluctuations were first established, and then shown to be organized by the large-scale coronal magnetic field (Woo and Gazis, 1993). Simultaneous measurements of density and density fluctuations based on Ulysses ranging measurements demonstrated that the large variations in density fluctuations were reflected similarly in the fractional density fluctuations ($\Delta n/n$, where n is electron density) (Woo et al., 1995a). These first measurements of fractional density fluctuations are also significant because fractional density fluctuations were previously thought not to vary much throughout the solar wind (Houminer and Hewish, 1974; Coles et al., 1978; Tappin, 1986; Woo and Gazis, 1994).

Instances of enhanced density fluctuations observed near the neutral line were identified as stalks or extensions of coronal streamers (Woo et al., 1994; Woo et al., 1995a) and shown to represent filamentary structure by comparing measurements of one long-lived streamer over successive solar rotations (Woo et al., 1995b). These signatures of the coronal streamer have been traced to the orbit of Earth, where they have also been observed in direct plasma measurements but have undergone considerable evolution (Liddleston et al., 1995). Filamentary structures (ray-like structures, flux tubes, striations) apparently permeate the solar corona, as perceived in early studies of the solar wind (Parker, 1963; Michel, 1967; Burlaga, 1972). There is a continuous range of scales extending from the size of coronal streamers to structures as small as about 1 km at the Sun. The latter result has been determined from images of the electron density scatterers in the plane of the sky provided by angular broadening measurements (Win, 1995a). What makes the evidence for this important result even more compelling is the fact that it is consistent with changes in the electron density spectrum inferred from phase scintillation and spectral broadening measurements (Woo, 1995a). The ability to unambiguously distinguish temporal and spatial variations — not possible with in situ plasma measurements (Thieme et al., 1990) — is further testimony to the power of radio propagation measurements.

The smallest filamentary structure of size 1 km at the Sun corresponds to an approximate time scale of 1 sec (fluctuation frequency of 1 Hz) in intensity or phase/Doppler scintillations. Within these structures the electron density fluctuations are manifested as random electron density irregularities (turbulence) that are convected along the solar wind. It is the scattering from these irregularities that has made it possible to measure solar wind speeds with spaced-receiver observations of intensity scintillation (Coles, 1993). The ultra fine-scale structure and turbulence deduced from the radio propagation measurements is depicted in Fig. 1.

From radio propagation measurements, the picture of a corona highly structured in density — spanning large-scale structures observed by white-light coronagraphs down to

Scale. sizes as small as 1 km at the Sun - has spurred a search for corresponding solar wind speed structure. Not *surprisingly*, evidence for structure in solar wind speed based on spaced-receiver intensity scintillation measurements inside 10 R_0 has also been found (Woo, 1995t). That structures are observed in both radio propagation and white-light measurements reinforces the close association between these two types of measurements. This relationship is examined more closely in the following section.

III. RELATIONSHIP BETWEEN DOPPLER SCINTILLATION, RANGING AND WHITE-LIGHT MEASUREMENTS

The radio measurements of time delay $\Delta\tau$ (ranging) and phase ϕ observe the path-integrated electron density n

$$\Delta\tau \text{ or } \phi \sim \int n \, ds \quad (1)$$

while Doppler frequency f_D , the time. derivative of phase, observes the time derivative of the path-integrated density

$$f_D = \frac{d\phi}{dt} \sim \frac{d}{dt} \int n \, ds \sim \frac{d}{ds} \int n \, ds \quad (2)$$

where s is distance along the ray path. Time-delay scintillation $\sigma_{\Delta\tau}$ and Doppler scintillation σ_D , the rms of $\Delta\tau$ and f_D , respectively, are given as follows:

$$\sigma_{\Delta\tau} \text{ or } \sigma_D = \text{rms of fluctuations in } \frac{d}{ds} \int n \, ds \text{ or } \frac{d}{dt} \int n \, ds \quad (3)$$

and are therefore proportional to density fluctuations Δn (see e.g., Woo et al., 1995a).

Since the density variations (of fluctuation frequencies lower than about 1 Hz) are causal by structure, the time derivatives are equivalent to spatial gradients, where the temporal and spatial variations are related through the Sun's rotation rate. Hence, 1 Doppler frequency observes density gradient, and σ_1 observes the rms of the density gradient fluctuations.

When white-light coronagraph pictures are processed to enhance density gradients, they have revealed a variety of striking ray-like structures that are not always readily discernible in the original pictures (Koutchmy, 1977; Guhathakurta and Fisher, 1995). The results in (1)-(2) show that, while time delay is similar to the white-light measurements of polarized brightness pB , 1 Doppler frequency is the counterpart of the white-light pictures processed to enhance density gradients (Woo et al., 1995b). This is illustrated in Fig. 2, showing profiles of time delay and 1 Doppler frequency across the extension or stalk of a coronal streamer observed at $1.4 R_\odot$ by Ulysses (Woo et al., 1995b). The once per hour sampling rate of the Doppler frequency measurements corresponds to a spatial resolution of about 10 arcsec - - roughly the resolution of the Spartan 201-01 pictures displayed in Fig. 1 of Guhathakurta and Fisher (1995). Comparison of the profiles in Fig. 2 with cuts across the streamers of these Spartan 201-01 white-light coronagraph measurements indicates remarkable similarity. Fig. 2 shows that across the stalk of the coronal streamer there are several alternating peaks and nulls in the density gradient (corresponding to the several bright and dark rays seen in the Spartan pictures for which density gradient is enhanced) with a null (dark ray) occurring at the peak of the density.

Raising the sampling rate of the Doppler frequency measurements in Fig. 2 increases the spatial resolution of the measurements of the coronal streamer. Shown in Fig. 3 are the measurements for sampling rates of one per hour, one per 10 mins, one per 1 min, and one per 10 secs, corresponding to spatial resolutions roughly 10 arcsec, 1 arcsec, 0.1 arcsec and 3×10^{-2} arcsec at the Sun, respectively. The rise in the number of fluctuations, together with the nearly continuously alternating sign of the density gradient (measured by

1 Doppler frequency), indicates that increasingly finer filamentary structures are observed as the spatial resolution is improved. Since Doppler scintillation is the rms of Doppler frequency computed over 3 mins based on measurements sampled every 10 SCC (Woo et al., 1985), it represents the rms of the variation in density gradient computed over a longitudinal distance of 340 km (0.5 arcsec) at the Sun based on gradient measurements every 20 km (3×10^{-2} arcsec). Since the filamentary structures in the corona extend to scale sizes as small as 1 km at the Sun, Doppler scintillation represents a new tool for studying structures that are remarkably two orders of magnitude smaller than those observed previously (Koutchmy et al., 1994; Habbal, 1992).

Insight into the relationship between density (as measured by ranging or time delay) and small-scale density structure (Doppler scintillation) is illustrated in Fig. 4. Measurements of time delay $\Delta\tau$ and rms Doppler scintillation σ_D from the egress portion of the 1991 superior conjunction of Ulysses (Woo et al., 1995a), along with the corresponding values of $\Delta n/n$ in percentage deduced from them, are displayed. The egress period covered day of year (DOY) 233-248 during which both coronal streamer and low latitude coronal hole regions were probed over a heliocentric distance range of 4-40 R_\odot . Several important features about the solar corona and radio measurements are evident. First, radial dependence dominates the measurements of both density and small-scale density structure, and it is necessary to remove it before useful comparisons with solar features can be carried out, as was recently demonstrated (Woo and Gazis, 1993; Woo et al., 1995a). This is equivalent to the use of radially graded filters in the case of eclipse pictures. Second, to compare radio and solar observations in a meaningful manner, the radio measurements should have as few data gaps as possible. Third, variation in small-scale structure Δn is extensive (one to two orders of magnitude) - the small-scale structure is large in coronal streamers and small in coronal hole regions (Woo et al., 1995b). However, the small-scale structure is small when compared to density, with $\Delta n/n$ amounting to only a few tenths to a few percent. Although $\Delta n/n$ is small, its variation, like

that of Δn , is large. Similar results for Δn and $\Delta n/n$ have been obtained for larger-scale structure [rms of 10 min ranging measurements over 5 hr spans (Woo et al., 1995a)]. Fourth, since $\Delta n/n$ is small, the measurement of density (ranging) essentially observes the large-scale coronal structure. However, owing to the relatively small variation of large-scale structure - Only about a factor of two --- large-scale structures, e.g., coronal streamers and plumes, can be masked by the radial dependence of ranging measurements. As will be shown later, removal of the dominant radial variation of the ranging measurements in Fig. 4a reveals plumes in all equatorial coronal hole region.

Since $\Delta n/n$ is small, increasing the sampling rate of the ranging measurements in Fig. 2a does not alter the density profile of the coronal streamer. However, as with the low-contrast larger-scale structures observed in white-light pictures of density [Fig. 1a of Guhathakurta and Fisher (1995)], the low-contrast small-scale structures in the ranging measurements of Fig. 2a can be seen more clearly either by removing the background density [equivalent to high pass filtering the white-light measurements - Fig. 1c of Guhathakurta and Fisher (1995)] or by displaying the time derivative of time delay as in Fig. 2b showing Doppler frequency [equivalent to enhancing density gradients - Fig. 1b of Guhathakurta and Fisher (1995)].

Radio propagation measurements provide high spatial resolution measurements of coronal structure in the Sun's longitudinal direction, and hence complement the plain-of-the-sky eclipse and white-light coronagraph measurements. It is important to point out that both ranging and Doppler scintillation measurements have superior remote sensing capabilities, not only because they sense structure that is orders of magnitude smaller than that by white-light measurements, but also because the radio measurements possess a substantially wider dynamic range, higher sensitivity and lower uncertainty. It is these features that permit the radio measurements to often observe the solar corona from the vicinity of the Sun to as far as near 1 AU (Woo, 1978). Hence, even if the spatial resolution of white-light measurements were to be improved, unless the aforementioned

features are present, small-scale structure may still not be observed because of its low contrast and large differences between streamer and coronal hole regions. One of the ironies that has emerged in the new understanding of the radiopropagation measurements is the fact that, while white-light measurements suffered from lack of spatial resolution, the ‘resolution’ of the most extensively observed radio measurement – intensity scintillation – was too high. Intensity scintillation mainly observed the turbulence inside the smallest structure but not the structure itself (Woo, 1995a).

Although the use of Doppler scintillation for observing and studying small-scale structure is an important new development, the use of ranging measurements for investigating large-scale structure such as coronal streamers and plumes is equally significant, as will be demonstrated. Shown in Fig. 5 are the IIAO Mauna Loa Solar observatory Mk III K-coronameter synoptic maps (courtesy of J. Burkepile at IIAO) based on polarized brightness (PB) measurements on the west limb at heights of $1.36 R_{\odot}$ and $1.74 R_{\odot}$ (see e.g., Sime et al., 1990) and covering Carrington rotations 1845 and 1846. During this time, Ulysses was also probing the corona at higher altitudes off the west limb. The black dots on the K-coronameter maps, which represent the closest approach points of the Ulysses radio path mapped back to the Sun, indicate that during the period of DOY 241–248, Ulysses probed an equatorial coronal hole region. The Ulysses time delay measurements during this time are displayed in Fig. 6a in reverse time order for the convenience of comparison with the K-coronameter maps. Corresponding radial distances are marked at the top of the panel showing that the measurements took place in the range of $20-401 R_{\odot}$. These data are a subset of the measurements shown in Fig. 4a. To remove the radial dependence, the measurements in Fig. 6a have been multiplied by $(R/1 \text{ AU})^{1.42}$ (Bird et al., 1994), where R is heliocentric distance in AU, and the results displayed in Fig. 6b. A quadratic fit to remove the additional background density is applied to these data and the difference is displayed in Fig. 6c. The time delay measurements are so precise that their measurement error bars are smaller than the size of the data points. This is not the

case with white-light measurements for which uncertainties can be substantial (Fisher and Guhathakurta, 1995).

Like white-light measurements of polarized brightness, time delay observes density, and the variations in Fig. 6 appear systematic. The variations in Figs. 6b and 6c (magnitude of variations, frequency of peaks, and angular size of peaks) bear striking resemblance to the corresponding latitudinal profiles of polar coronal holes at 21° displayed in Figs. 2a (polarized brightness) and 2b (polarized brightness minus fit) of the Spartan 201-01 images (Fisher and Guhathakurta, 1995). This similarity indicates that plumes appear to be present not just in polar regions (Saito, 1965; Newkirk and Harvey, 1968), where remnants in interplanetary space may possibly have been detected by Ulysses in its passage over the south polar coronal hole (Phillips et al., 1995), but also in the open field coronal hole regions between streamers. Furthermore, they extend far beyond the corona observed in white-light measurements. These results are consistent with EUV measurements of the solar corona (Wang and Sheeley, 1995), as well as low-latitude plasma measurements by Helios near 0.3 AU (Thieme et al., 1990).

IV. CONCLUDING REMARKS

Integrating the results from (i) verse radio propagation measurements has led to significant gains in our knowledge of coronal structures, substantial improvement in our understanding of radio propagation measurements as a tool for remote sensing the corona, and clarification of the relationship between radio propagation and coronagraph measurements. The radio measurements confirm that streamers are ray-like structures as depicted in coronagraph pictures, but also show that there exists throughout the corona a hierarchy of filamentary structures that extends from the size of streamers down to scale sizes as small as about 1 km at the Sun (10^{-3} arcsec). Small-scale structures (sub-arcsec) that have long eluded coronagraph measurements can now be observed with Doppler scintillation measurements, while large-scale structures not yet observed by coronagraphs,

such as plumes in equatorial coronal hole regions, can be studied with high precision ranging measurements. The corona is obviously rich in structure, and additional details on its morphology can be expected as future investigations based on these unique radio measurements are conducted.

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FIGURE CAPTIONS

Fig. 1 Smallest filamentary structure of size 1 km at the Sun. Within these structures are random electron density irregularities (turbulence) that are convected along the solar wind.

Fig. 2 Profiles of time delay $\Delta\tau$ (density) and Doppler frequency f_D (gradient of density).

Fig. 3 Profiles of Doppler frequency (gradient of density) with increasing sampling rate and hence spatial resolution. The approximate corresponding spatial resolution is (a) 10 arcsec, (b) 1 arcsec, (c) 0.1 arcsec, and (d) 3×10^{-2} arcsec at the Sun.

Fig. 4 Radial variation of measurements of time delay (density), Doppler scintillation (density fluctuations) and $\Delta n/n$ by Ulysses during DOY 233-248 in 1991. The axes have the same orders of magnitude to allow convenient comparison. Neglecting the radial variation, the variation in density is about a factor of two, but the variation in density fluctuations and $\Delta n/n$ is one to two orders of magnitude.

Fig. 5 JIAO Mauna Loa Solar Observatory Mk III K-coronameter synoptic maps (courtesy of J. Burkepile at JIAO) based on polarized brightness measurements on the west limb at heights of $1.36 R_{\odot}$ and $1.74 R_{\odot}$. The black dots on the K-coronameter maps, which represent the closest approach points of the Ulysses radio measurements in Fig. 6 mapped back to the Sun, indicate that during the period of DOY 241-248, Ulysses probed an equatorial coronal hole region.

Fig. 6 Time series of (a) time delay $\Delta\tau$ by Ulysses ranging measurements (subset of data displayed in Fig. 4), (b) same as (a) but with radial dependence removed, (c) same as (b) but after quadratic fit has been removed. The time series in (c) is similar to that of the polar coronal plumes from the Spartan white-light pictures and shown in Fig. 2b of Fisher and Guhathakurta (1995).











